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DEPARTMENT REPORT
UWME-DR-901-102-1

HYGROTHERMAL RESPONSE OF POLYMER MATRIX COMPOSITE MATERIALS

FINAL REPORT

DONALD F. ADAMS
DAVID E. WALRATH

SEPTEMBER 1979

U.S. ARMY RESEARCH OFFICE
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A two-dimensional, generalized plane strain, finite element analysis of the stress states in the individual fibers and surrounding matrix of a unidirectionally reinforced composite material was developed. The fibers are modeled as elastic but anisotropic; the matrix is modeled as isotropic, but elastoplastic. Thermal and moisture absorption histories as well as temperature - and moisture-dependent material properties are included. A complete finite element computer program, an associated plot package, and extensive

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numerical results are available.

Experimental work was conducted using unreinforced (neat resin), castings of Hercules 3501-6 epoxy matrix, as well as AS/3501-6 graphite/epoxy matrix, and S2/3501-6 glass/epoxy unidirectional composites. Axial and transverse tensile tests as well as torsional shear tests were performed, under various temperatures and moisture conditions.

Experimental results and comparisons with micromechanics predictions are summarized, with references given to various conference and journal publications for detailed information.

Foreword

This Final Report summarizes research conducted during a three-year study performed under sponsorship of the U.S. Army Research Office, Durham, North Carolina, which was initiated in February, 1976. The first two years were performed under Grant DAAG 29-76-6-0163, the third year under continuation Grant DAAG 29-78-G-0053. The ARO Program Monitor during the entire period was Dr. John C. Hurt, Associate Director, Metallurgy and Materials Science Division.

Program Manager and Principal Investigator at the University of Wyoming was Dr. D. F. Adams, Professor of Mechanical Engineering. Co-Principal Investigator during the first half of the study was Dr. A. K. Miller, Assistant Professor of Mechanical Engineering. Co-Principal Investigator during the second half of the study was Mr. D. E. Walrath, Staff Scientist in Mechanical Engineering

Graduate students making significant contributions included M. M. Monib, B. G. Schaffer, S. R. Graves, R. A. Benson, S. V. Hayes, D. A. Crane, and M. N. Irion. Undergraduate students included A. R. Hoyt, R. S. Zimmerman, K. M. Kiger, and D. W. Peterson.

CONTENTS

Section 1

Statement of the Problem

There has been a considerable increase in interest during the past five years in the influence of moisture on the mechanical properties of polymer-matrix composite materials. The present study was actually initiated in late 1974, with the preliminary formulation of an inelastic micromechanics analysis to model moisture expansion effects and moisture-dependent material properties. Support by the Army Research Office was made available in early 1976. At that time, very few reliable experimental data were available in the literature. Many of the published data were conflicting. However, enough was known to verify the assumption that moisture absorption has much the same influence on a polymer as an increase in temperature. That is, the nonlinear response is enhanced, with modulus and strength decreasing, and strain to failure increasing. Thus, a nonlinear analysis was called for.

The study being reported here was limited to time-independent inelastic material response. This has been referred to as elasto-plastic material behavior. Viscoelastic/viscoplastic material response, i.e., time-dependent response, is the subject of a follow-on study presently being initiated [1].

Because of the complexity of the problem, a numerical analysis was clearly in order. Since a fundamental understanding of the influence of changes in the mechanical properties of the polymer matrix on the composite response was desired, a micromechanical

approach was necessary. That is, a study was made of the local stress and deformation states in and around individual fibers.

Micromechanical analyses of composite behavior had been performed previously, including several by the present senior author. Most of these had assumed elastic material behavior, however, and also isotropic fibers. No prior analyses included moisture effects, or varying material properties. A survey of these prior works is presented in Reference [2].

Thus, the goal of the present study was to develop a rigorous micromechanical analysis of a unidirectionally reinforced composite material subjected to any combination of normal stresses, thermal histories and moisture exposure histories. Actual matrix stress-strain relations, to be determined experimentally, were to be used as input properties. This would require the determination of the polymer matrix properties over the full temperature and moisture ranges of interest. Since simple superposition could not be assumed, this implied that properties would have to be determined at combinations of temperature and moisture conditions.

Since graphite fibers as well as some other commonly used reinforcements (e.g. Kevlar) were known to be both mechanically and thermally anisotropic, fiber anisotropy was to be modeled.

In order to permit axial loadings (i.e., applied stresses in the fiber directions) and yet retain the advantages of a two-dimensional analysis, it would be necessary to convert prior plane analyses to a generalized plane strain condition.

Finally, in order to be able to interpret the results obtained, and to present them in an easily understandable manner, extensive computer graphics would have to be developed.

All of these goals were achieved during the three-year study being reported here. Some of the more significant results are summarized in the next section.

Section 2

Summary of Results

2.1 First Year

The full first year of the study was directed to developing the basic analysis, the associated finite element formulations and computer program, and a preliminary data output plot routine. A detailed survey of the literature relating to temperature- and moisture-dependent polymer matrix material properties was also completed. The analysis work had actually been initiated prior to the beginning of the first year, permitting a technical report to be prepared in January 1979 [2]. This technical report includes a detailed historical review of the problem, a full presentation of the governing equations, details of the finite element formulation and a few numerical examples and check cases. It provides a complete source of information concerning the fundamentals of the analysis approach.

Although some experimental work was also initiated during the first year, including the fabrication and testing of neat resin specimens of Hercules 3501-5 and 3501-6 epoxy, sufficient data were not available for use as input to the micromechanics analysis. Thus, an amalgom of these limited data and available literature results was used as input in generating the brief results reported in Reference [2]. These assumed input curves are also presented in Reference [2]. In retrospect, the assumed curves were not very accurate; the degree of nonlinearity and the strain to failure were overestimated, particularly for the elevated temperature, dry conditions.

2.2 Second Year

The generation of suitable experimental data was emphasized during the second year. The Hercules 3501-5 and 3501-6 epoxy matrix systems were found to have essentially identical mechanical and physical properties, as expected. The handling properties were also very similar, however. Thus, it was decided to conduct the remainder of the experimental work with the newer and more widely used 3501-6 system. Being a hot melt system, casting of thin (1.3 mm, i.e., 0.050 in.) plates and 6.3 mm (0.25in.) diameter rods which were free of trapped air bubbles, for use in making test specimens, turned out to be a major problem. Considerable effort was expended in developing a technique for making high quality specimens. This is discussed in detail in Reference [3], along with neat resin test data for the Hercules 3501-6 epoxy matrix material.

AS/3501-6 graphite/epoxy and S2/3501-6 glass/epoxy unidirectional conposites were also fabricated and tested during the second year. The AS graphite fiber is a low modulus (220 GPa i.e., 32 Msi) fiber produced by Hercules, Incorporated [4]. AS/3501-6 prepreg in 300 mm (12 in.) wide rolls was purchasedfrom Hercules, and fabricated into flat panels or molded into 6.3 mm (0.25 in.) diameter rods (for torsion testing). Details of the fabrication processes are presented in Reference [5]. Since S2/3501-6 glass/epoxy prepreg was not available and it was desired to use the same matrix resin system throughout the study, S2 glass fiber roving was purchased from Owens Corning Fiberglas Corporation [6] and prepregged with the Hercules 3501-6 epoxy matrix.

The Composite Materials Research Group routinely prepregs its own materials and thus this did not present any special difficulties. Details of both the prepregging process and fabrication of panels and torsion rods are presented in Reference [5].

Longitudinal and transverse tensile as well as torsional shear tests were conducted on both composite material systems. Both dry and fully moisture saturated specimens were tested, at room temperature and at several elevated temperatures up to 160°C (320°F), the Hercules 3501-6 epoxy being a 177°C (350°F) cure system. These test results are presented in Reference [5]. Neat resin specimens were also tested at these same temperatures and moisture conditions [3].

The properties of the neat resin are not of major interest in the structural applications sense, composites rather than unreinforced polymers being the main thrust of the present study. However, full knowledge of the neat resin properties is fundamental to the meaningful use of the micromechanics analysis for predicting composite material response. Because polymers such as the Hercules 3501-6 epoxy are essentially never used in unreinforced forms, there are almost no properties data available in the literature.

Because of this, as discussed in Section 2.1, for the first-year analytical work, the matrix properties were estimated.

During the second-year study, while experimental data were being generated, many additional refinements of the basic micromechanics analysis and computer program were incorporated. Many of these refinements were made as a result of deficiences discovered while using

the analysis for various applications purposes. In particular, a better method of tracking the input stress-strain curves of the matrix was developed. Also, an entirely new plot package was written, in order to be able to present results in a clearer manner.

These various additions and modifications are summarized in Section 3, and serve to update Reference [2].

2.3 Third Year

During the third year the experimental work was completed. This made available, for the first time, a reasonably detailed and self-consistent set of data for use in the micromechanics analysis. The Richard-Blacklock curve-fit procedure used in the original numerical analysis, as discussed in Reference [2], was computerized. Since the experimental data were acquired in digital form using a computer-controlled testing machine (an Instron Model 1125 electomechanical test machine controlled by a Hewlett-Packard 21MX-E minicomputer) and stored on a magnetic tape, it was possible to develop software to take this actual data and convert it into a form which can be input directly into the micromechanics analysis computer program with no manual data preparation required. This capability was made fully operational during the third year.

These data were then used as input to the micromechanics analysis to predict the response of the graphite- and glass-fiber reinforced unidirectional composites. Detailed comparisons were made between predicted and experimentally measured elastic moduli, Poisson's ratio, and coefficients of thermal expansion as functions of both temperature and moisture content. These comparisons are presented and discussed in Reference [7].

In addition, the experimental data for the neat resin were used to repeat some of the micromechanics calculations made during the first two years of study using assumed matrix material properties. Predicted moisture expansion and thermal expansion coefficients for high, medium and low modulus graphite fiber-reinforced composites incorporating the Hercules 3501-6 epoxy matrix are presented in Reference [8].

Increasing interest in identifying failure modes and causes of failure prompted a study of the temperature- and moisture-induced normal and shear stresses at the fiber/matrix interface. High, medium, and low modulus graphite fibers, and S2 glass fibers, in the Hercules 3501-6 epoxy matrix were studied. Results are presented in detail in Reference [9]. This study during the third year prompted the addition of an interface plot routine to the micromechanics computer program plot package. This routine was used to obtain all of the results presented in Reference [9].

Another area of interest which was brought to the Composite Materials Research Group's attention during the third-year study was the concern by polymer chemists in synthesizing resins which have mechanical properties leading to improved composite performance. In particular, polymers having high strain to failure are being proposed for use [10]. As a result of discussions with the senior author of Reference [10] and other polymer chemists during the Second Annual Army Composite Materials Research Review at the University of Massachusetts in May 1979, and during earlier conferences, it was decided to use the micromechanics analysis to study the potential benefits of these potential matrix materials. Some typical results are presented in Reference [11]. Additional studies are planned.

The micromechanics analysis was also used to generate unidirectional ply material properties for use in structural applications where all of the required properties were not known. One such application is reported in Reference [12]. Composite materials are finding increasing use in spacecraft optical structures, because of their reduced weights and extremely low thermal expansion coefficients in certain laminate orientations. In fact, the thermal expansion coefficients are often so low (on the order of $10^{-8}/°C$ or less) that they are extremely difficult to determine experimentally. These values can be predicted using the micromechanics analysis in conjunction with a classical laminated anisotropic plate analysis, starting with known constituent material properties (i.e., fiber and matrix properties). These constituent material properties are not typically extremely low, and hence can be measured reasonably accurately by conventional methods.

The spacecraft operates in the vacuum of space, where no moisture is present. However, it is fabricated, checked out, and its optical systems calibrated on earth, a process which requires several years. During this time period, the composite material is subjected to various levels of relative humidity, causing the structure to continually swell and shrink. The moisture diffusion process is slow; it can take several years in a vacuum at room temperature for a composite of even moderate thickness to desorb this moisture. Thus, it is important to be able to predict this moisture expansion history, so that the optical system can be calibrated accordingly. Since moisture expansion coefficients are not yet commonly measured experimentally, few data are available in the literature. The micromechanics analysis has been used very effectively to predict these values [12].

During the third year, the micromechanics computer program was provided to both the Army Materials and Mechanics Research Center (AMMRC) and the University of Bristol. AMMRC personnel visited the University of Wyoming in January 1979 to learn to use the program. The program is available to others for use as well, upon request, being fully operational at this time.

During the third year of the study, a large blanket press was designed and construction initiated. This press is nearing completion at the present time. It will be capable of curing a composite component up to 30" x 30" in size. Cost of the construction materials was supported by the ARO Grant. Fabrication labor is being provided by the Mechanical Engineering Department. This blanket press facility, when operational,will greatly expand the Composite Materials Research Group's fabrication capabilities.

Section 3

Micromechanics Computer Program Modifications

Details of the basic micromechanics theory developed during the present study, and a general description of the associated finite element numerical solution technique and corresponding computer program, were presented in Reference [2]. During the final two years of the study, a number of refinements were incorporated, however. To assist the interested reader in understanding the direction these modifications have taken, they are summarized briefly in the following paragraphs.

Complete documentation of the micromechanics computer program, including detailed instructions for its use, is available from the Composite Materials Research Group at the University of Wyoming.

The basic formulation outlined in Reference [2] remains unchanged. Modifications have been made primarily to improve accuracy or ease of use.

Since the program is used primarily to analyze square arrays of circular fibers, a fixed finite element grid is available. A specified fiber volume content can be input and the program will scale this grid accordingly, thus eliminating the need to reconstruct a grid for each use.

Since an incremental loading solution is used, it is possible to terminate the computer run at the end of any load increment, store the necessary data and then restart it at some later time. This also permits branching from any point. For example, having simulated the thermal residual stresses induced during curing, it may be desireable to study the subsequent response to several different loading conditions, with or without the subsequent addition of moisture. The restart capability

permits the analysis of these different conditions without the necessity of repeating any prior common loading increments, resulting in significant savings in computer run time.

The definitions of octahedral shear stress and octahedral shear strain have been reexpressed in forms more suitable for computer use. The definition of the initial slope of the octahedral shear stress - octahedral shear strain curve has also been modified accordingly.

In the initial analysis and computer program, failure of the fiber was defined in the same manner as the matrix material, viz, as occurring when the octahedral shear stress (or octahedral shear strain) at any location within the fiber was exceeded. As more extensive micromechanical analyses of anisotropic graphite fibers were performed, it was found that an octahedral criterion (which is essentially a distortional energy criterion) was not adequate. The criterion was reexpressed in terms of material principal stress allowables, which now reflects the anisotropy more accurately.

In the initial program, coefficients of thermal expansion and moisture expansion were not calculated and output, although composite strain increments were available. The program now computes and prints out the thermal expansion coefficients for any incrments in which a temperature change only is applied, and the moisture expansion coefficients for any increment in which a moisture change only is applied.

The normal and shear stresses around the fiber/matrix interface are now also calculated and stored for plotting purposes.

A complete printout of the stress state in every finite element for every loading increment results in a large volume of output, much of which may not be needed. Thus, it is possible to specify only those

increments for which a full printout is to be provided. However, it may be desireable to trace the loading path of a particular element throughout the entire loading history. For example, if a particular material region is successively loading and unloading, or the temperature and/or moisture is continually changing, it may be desireable to verify that the material response is following the specified input stress-strain curves. The present version of the program permits the specification of an element for which complete information is printed for every solution increment.

The data output computer plotting routine has been completely revised since Reference [2] was written. At that time only the principal stresses were plotted, as vectors originating at the centroid of each finite element. The directions of the in-plane principal stresses were indicated by the directions of the vectors, while the third (out of plane) principal stress was plotted as a vector at an angle of 135° from the positive x-axis. The magnitudes of these three stresses were indicated by the lengths of the vectors. Negative values were indicated if the arrowhead pointed at the centroid rather than away.

In the present plot package, contour plots are used to portray these three principal stresses and three additional quantities of interest, i.e., octahedral shear stress, octahedral shear strain, and the in-plane shear stress. Also, radial plots of the normal stress and the tangential shear stress around the fiber/matrix interface are available. By specifying the plots wanted, any combination of these eight plots, for any combination of loading increments, can be obtained.

The availability of this extensive plotting capability makes it almost unnecessary to even refer to the printed output.

Although not part of the present ARO study, three major additions to the Micromechanics analysis and associated computer program are currently in progress. Under Army Materials and Mechanics Research Center (AMMRC) sponsorship [13], a longitudinal shear loading capability is being added. That is, it will then be possible to study the influence of shear loads applied parallel to the fiber axes, as well as normal loadings.

Nonlinear viscoelastic material response is also being added. This has been proposed as a task under the ARO Grant described by Reference [1]. Although the grant has not yet started, work on the viscoelastic analysis has, as an in-house effort.

Under a NASA-Lewis Grant [14], presently in its second year, crack initiation and propagation is being added to the micromechanics analysis. This will permit the study of micromechanical response beyond first failure, to total failure of the unidrectional ply. The eventual goal is to develop a physical failure criterion, to support or replace the phenomonological failure theories in present use.

Section 4

Abstracts of Publications of Results

A significant number of journal publications, published conference proceedings, and unpublished conference and technical meeting presentations have been prepared based upon the research work performed for ARO to date. Additional publications are planned.

Brief abstracts of these publications and presentations are presented here. Copies of the complete papers are, or will be, available from the Composite Materials Research Group.

4.1. Reports

A.K. Miller and D.F. Adams, "Micromechanical Aspects of the Environmental Behavior of Composite Materials", Report UWME-DR-701-1111, Mechanical Engineering Department, University of Wyoming, January 1977.

This report begins with a literature survey of numerous investigations of the effects of moisture on fiber-reinforced composites fabricated using polymeric materials as the matrix constituent. It is noted that for certain conditions, the results reported by different investigators shown seemingly anomalous property increases for composites when they are subjected to high moisture and temperature environments. These property increases are postulated to be the result of moisture-induced dilatational strains within the matrix material, which relieve the thermally induced (curing) residual microstresses in the material. The survey reveals no previous analytical efforts to account for the effects of both thermal-and moisture-induced strains on the microstress state of a composite, nor for the temperature and/or moisture dependence of the constituent material properties.

A finite element analysis method is developed to analyze the micromechanical stress state in a fiber-reinforced composite. The method is based on generalized plane strain conditions, which permits a pseudo-three-dimensional analysis. Nonlinear (plastic) material behavior is included, which requires that the analysis utilize incremental loading parameters. The constitutive relationships for isotropic plastic matrix material behavior are formulated for both plane strain and generalized plane strain conditions, with hygrothermal dilatation strains included, as are the constitutive equations for transversely isotropic elastic fiber material behavior.

A unique aspect of the analysis method presented in this report is the inclusion of the functional dependence of the constitutive material properties on temperature and/or moisture. A method of solving the resulting global equations is used which allows all external tractions to be applied simultaneously. The solution method permits an extremely efficient incremental analysis routine to be developed. The fact that the material properties are not constant, but functions of the environmental state, requires that changes in the environment also be modeled in small incremental steps. The analysis method permits the environmental changes to be simultaneously applied along with the external loading increments.

Examples of applications of the analysis method are presented. Transverse loading of a unidirectionally-reinforced boron/aluminum composite is analyzed, and the results compared to those reported by previous investigators. Transverse and axial loadings of a graphite/epoxy composite are also analyzed. The effects of temperature and

moisture changes on the microstresses in the composites are presented, based on idealized mechanical properties of the epoxy. It is shown that, in some cases, moisture dilatation of the matrix material can relieve local residual curing stresses sufficiently to result in a net increase in composite strength properties of a polymer-matrix composite.

4.2 Journal Publications

D.F. Adams and A.K. Miller, "Hygrothermal Microstresses in a Unidirectional Composite Exhibiting Inelastic Material Behavior", Journal of Composite Materials, Vol. 11, No. 3, July 1977, pp. 285-299.

A finite element numerical analysis is presented which models the influences of temperature variations and dilatations due to moisture absorption on the local stress state in a unidirectionally-reinforced composite material. These influences are admissible in both fiber and matrix, and all material properties are assumed to be temperature- and moisture-dependent. The fiber is assumed to be elastic and transversely isotropic, the matrix material inelastic and isotropic. A generalized plane strain condition is formulated, which permits the analysis of applied normal loadings in three directions (i.e., longitudinal and biaxial transverse) combined with arbitrary temperature and moisture content changes. Numerical results are presented for a typical graphite/epoxy composite, indicating the residual microstresses induced during cooldown from the curing temperature, and how they can be altered by a subsequent moisture absorption at room temperature. Results are also given for predicted microstress states and failure initiation in a graphite/epoxy composite modeled both with and without curing stresses and moisture dilatation, for a transverse normal applied loading continued beyond the elastic limit, to first failure.

D.F. Adams and A.K. Miller, "The Influence of Material Variability on the Predicted Environmental Behavior of Composite Materials," Journal of Engineering Materials and Technology, Vol. 100, No. 1, January 1978, pp. 77-83.

The stresses and strains induced in a composite material when subjected to mechanical loads are shown to be strongly influenced by prior exposure to both temperature changes (e.g., cooldown from the curing temperature) and moisture absorption (e.g., even normal exposure to ambient conditions after cure). These environmental effects are in turn influenced by normal variabilities in the basic properties of the composite constitutents.

Using a recently developed finite element numerical model of composite material inelastic hygrothermal response, variations in stresses and strains are predicted as a function of variations in constituent material properties. A typical graphite/epoxy composite is selected for detailed study. This system is of particular interest because of the anisotropic nature of graphite fibers, and the strong temperature and moisture dependence of the epoxy matrix. Specific fiber property variations considered include transverse modulus, major Poisson's ratio, and in-plane Poisson's ratio. Results are compared with those obtained for an isotropic fiber composite.

A.K. Miller and D.F. Adams, "Inelastic Finite Element Analysis of a Heterogeneous Medium Exhibiting Temperature and Moisture Dependent Material Properties", Fibre Science and Technology, Vol. 12, No. 5, September 1979.

A pseudo-three-dimensional finite element method is presented for the analysis of the microstress state within a fiber-reinforced material. The method is based on a slightly revised definition of the generalized plane strain conditions. The analysis includes both inelastic and anisotropic

(transversely isotropic) material properties. The necessary material matrices for elastic isotropic, inelastic isotropic, and elastic anisotropic material behavior are given under the conditions of generalized plane strain. A unique aspect of the analysis is that environmental dilatational strains are included in the inelastic constituent material formulations.

The dependence of the material properties on temperature and/or moisture is extended into the inelastic material range. A means of incorporating these hygrothermally dependent material properties by using the Richard-Blacklock parametric modeling equations is introduced. A numerical example showing the importance of including the temperature dependence of the constitutive material properties when analyzing a fiber-reinforced composite material is presented.

D.F. Adams and M.M. Monib, "Contributions of the Polymer Matrix to the Hygrothermal and Mechanical Response of a Composite material," to be published in The Journal of Rheology.

The development of composite materials during the past several decades has emphasized the improvement of fiber properties. However, the polymer chemist is beginning to ask, "How can the matrix be modified to further improve the performance of the composite?" Since the polymer matrix typically exhibits at least some degree of nonlinear response prior to failure, and is subject to a very complex stress state induced by the fibers present in the composite, determination of the contribution of the matrix is a complex process.

Concurrently theoretical methods of predicting the response of a composite have been considerably refined during the past few years. In particular, the so-called micromechanics analyses, which predict the composite response of a unidrectional ply as well as the local stress states in fiber and matrix, are applicable to the title problem.

One such micromechanics analysis, developed by the author and his colleagues, has been used to predict the influences of variations of the polymer matrix properties on composite response to various combinations of temperature, moisture and applied loadings.

Basic experimental data are available for the epoxy matrix materials in current use, including complete stress-strain curves to failure for various test temperatures and moisture contents. The influence of specific variations of this matrix behavior have been modeled, to identify those modifications of the polymer which, if achieved, would improve the performance of the resulting composite. Variations considered include matrix modulus, ultimate strength, strain to failure, coefficient of thermal expansion, coefficient of moisture expansion, and the temperature- and moisture-dependence of these matrix properties, as well as matrix volume content of the composite.

The results obtained give the polymer chemist firm guidelines as to the directions the development of polymers should take in order to result in composite materials having improved performance in a particular environment and loading state.

4.3. Published Conference Proceedings

A. K. Miller and D.F. Adams, "An Inelastic Micromechanical Analysis of Graphite/Epoxy Composite Subjected to Hygrothermal Cycling," ASTM Conference, "The Environmental Effects on Advanced Composite Materials", Dayton, Ohio, September 1978.

Results are presented of an inelastic finite element analysis of the residual microstress state in a unidirectional graphite/epoxy composite subjected to temperature cycling from room temperature (294 K) to 405 K or a combined cycle of changing matrix moisture content from a saturated condition (5.6 percent water by weight) to 2.0 percent moisture content

with a simultaneous temperature change from room temperature to 339 K. In the analysis, the graphite fibers are modeled as being transversely isotropic, and assumed temperature- and moisture-dependent properties of modulus and strength for epoxy are utilized.

The results indicate that relatively large residual microstresses result from the cooldown of the composite from the curing temperature (450 K) to room temperature, and that in portions of the matrix material the residual stresses nearly exceed the yield strength of the material for a 60 percent volume composite. It is shown that moisture saturation of the matrix causes matrix yielding in both 40 and 60 percent fiber volume composites. It is noted that subsequent thermal cycling, or hygrothermal cycling, promotes definite changes in these microstress states which cause dimensional instability of the composite.

D.F. Adams, "Influences of Environment on the Dimensional Stability of Fiber-Reinforced Composite Structures", Proceedings of the Conference, "Environmental Effects and Degradation of Engineering Materials", VPISU, Blackburg, VA, October 1977.

A finite element micromechanical analysis is used to study the dimensional changes induced in a unidirectionally-reinforced composite due to variations in temperature and moisture content. A typical graphite/epoxy composite is assumed. The sensitivity of these predicted dimensional changes to variations in various constituent material properties is indicated. The presence of absorbed moisture is shown to have a significant influence on the apparent thermal expansion properties of the composite under certain conditions. The effect of moisture dilatation on the subsequent mechanical loading stress-strain response is also indicated.

D. F. Adams and M. M. Monib, "Moisture Expansion and Thermal Expansion Coefficients of a Polymer-Matrix Composite Material," Proceedings of the Fourth Conference on Fibrous Composites in Structural Design, San Diego, California, November 1978.

The influence of variations in fiber and matrix constituent material properties on the moisture and thermal expansion coefficients of a unidirectional composite is demonstrated, using a finite element, inelastic micromechanics analysis. Three of the commonly utilized graphite/epoxy material systems are selected for detailed analysis, using available experimental values of the constituent material properties wherever possible. The epoxy matrix is assumed to be Hercules 3501-6 in all cases, a polymer which is fully representative of the various structural epoxies in current use. The three graphite fibers are Celanese GY-70, Hercules HMS, and Hercules AS, representative of high, medium, and low modulus graphite fibers, respectively.

The analysis includes the influences of fiber anisotropy, matrix inelasticity, temperature- and moisture-dependent matrix material properties, variations in matrix thermal expansion and moisture expansion coefficients, and fiber volume content. Results are presented for both longitudinal and transverse coefficients of thermal expansion as a function of temperature, and the corresponding coefficients of moisture expansion as a function of composite moisture weight gain.

D. F. Adams, "Temperature- and Moisture-Induced Normal and Shear Stresses at the Fiber/Matrix Interface in Various Composite Materials," Proceedings of the 24th National SAMPE Symposium & Exhibition, San Francisco, California, May 1979.

Using an elastoplastic micromechanics analysis, a study is made of the local stresses induced in a composite, particularly at the fiber/

matrix interface, due to cooldown from the cure temperature and subsequent moisture absorption. Four polymer-matrix composites are analyzed, representative of high, medium, and low modulus graphite fibers and S glass fibers in a typical structural epoxy matrix. Actual properties of GY-70, HMS, and AS graphite fibers, S glass fibers, and Hercules 3501-6 epoxy are used, assuming a 60 percent fiber volume.

D. E. Walrath and D. F. Adams, "Moisture Absorption Analysis of the Thematic Mapper Graphite/Epoxy Composite Structure," in bound volume entitled Modern Developments in Composite Materials and Structures, ASME Winter Annual Meeting, New York, N.Y., December 1979.

Graphite/epoxy structures have been used in the Thematic Mapper to minimize thermally-induced dimensional changes. However, moisture absorption during fabrication and prelaunch assembly can also induce dimensional variations. These moisture-induced strains were predicted for the Thematic Mapper using a diffusion analysis, a micromechanics analysis, and a laminated plate stress analysis with the environmental conditions and material properties as input parameters. Changes were then suggested for controlling the prelaunch environment to minimize moisture-induced dimensional variations.

4.4 Seminars and Presentations

"Environmental Behavior of Polymer Matrix Composite Materials," Army Research Office Review of Degradation, Deformation, and Fracture of Polymers and Polymer-Based Composites, Wrightsville Beach, North Carolina, October 1976.

"Composite Materials: Influences of Property Variations on Performance," Westhollow Research Center, Shell Oil Company, Houston, Texas, May 1977.

"The Influence of Material Variability on the Predicted Environmental Behavior of Composite Materials," ASME Winter Annual Meeting, Atlanta, Georgia, November 1977.

"Hygrothermal Response of Polymer Matrix Composites," Eastman Kodak Company, Rochester, N.Y., February 1978.

"Hygrothermal Response of Polymer Matrix Composites," Workshop on the Effects of the Environment on Polymer Matrix Composites," U.S. Army Materials and Mechanics Research Center, Watertown, Massachusetts, May 1978.

"Laminate Analyses, Micromechanical Creep Response, and Fatigue Behavior of Polymer Matrix Materials," Second Annual Army Composite Materials Research Review, University of Massachusetts, Amherst, Massachusetts, May 1979.

4.5 Publications Planned

D. F. Adams and D. E. Walrath, "Experimental Data for Hercules 3501-6 Epoxy Resin as a Function of Temperature and Moisture."

D. E. Walrath and D. F. Adams, "Hygrothermally Influenced Mechanical Properties of AS/3501-6 Graphite/Epoxy and S2/3501-6 Glass/Epoxy."

D. F. Adams and B. G. Schaffer, "Micromechanics Predictions Versus Experimental Measurements of Unidirectional Composite Properties."

Section 5

Participating Scientific Personnel

The entire three-year study was under the general direction of Dr. D. F. Adams, who served as Program Manager and Principal Investigator. During the first year, Dr. A. K. Miller, initially a Ph.D. candidate and later a Supply Assistant Professor, served as a Principal Investigator also. Mr. D. E. Walrath, a Staff Scientist in the Composite Materials Research Group, took over as the second Principal Investigator during the final two years.

The basic micromechanics analysis and associated computer program was developed by Dr. Miller, as his Ph.D. Dissertation. Mr. Walrath has led most of the experimental aspects of this entire study.

These three Principal Investigators were assisted by a number of graduate and undergraduate students during the three years. Graduate students William Mentock, Melvin Glass and Joseph Milner contributed to the original computer programming and plot routines associated with the micromechanics analysis, working directly with Dr. Miller. Undergraduate students Ernie Gomez, Michael McGary, and Ross Benson did initial work in the experimental areas during this same time.

Ph.D. student Mohamed Monib took over the micromechanics analysis and related computer program during the second year, making substantial revisions and additions, some of which are outlined in Section 3. It was under his direction that the computer program became fully operational. He was assisted in developing the plotting routines by graduate student Michael Mills and undergraduate student Anthony Hoyt. More recently, graduate students Brent Schaffer and Daniel Murphy have made additional

changes and refinements, in the course of using the program for specific applications.

Graduate student Stanley Graves developed the basic procedure for converting the matrix experimental data to forms suitable as imput to the micromechanics analysis.

Mr. Walrath was assisted by a number of undergraduate and graduate students in various phases of the experimental work during the final two years of the study. Graduate students included Brent Schaffer, David Crane, Steven Hayes, Ross Benson, and Mark Irion, all of whom started their work as undergraduates. Participating undergraduate students included Forrest Selmer, Richard Zimmerman, Patrick Dempsey, Kevin Kiger, John Huenefeld, and David Peterson. Steven Payne, another undergraduate, worked on the data reduction computer program development during the third year. Undergraduate student Valerie Johnston assisted in computer program development with the analytical group.

Graduate student David Crane designed and supervised the construction of the blanket press, under the guidance of Mr. Walrath.

Full time mechanical Engineering Department staff members who made significant contributions to the study included Electronic Engineers George Twitchell and Robert Selman, and Computer Specialist Steven Ownbey.

References

1. "Laminate Analyses, Micromechanical Creep Response, and Fatigue Behavior of Polymer Matrix Composites," Army Research Office Grant, September 1979-March 1981.

2. A. K. Miller and D. F. Adams, "Micromechanical Aspects of the Environmental Behavior of Composite Materials," Report UWME-DR-701-1111, Mechanical Engineering Department, University of Wyoming, January 1977.

3. D. F. Adams and D. E. Walrath, "Experimental Data for Hercules 3501-6 Epoxy Resin as a Function of Temperature and Moisture," to be submitted for publication.

4. "Hercules Magnamite Graphite Fibers," Hercules Incorporated, Wilmington, Delaware, 1978.

5. D. E. Walrath and D. F. Adams, "Hygrothermally Influenced Mechanical Properties of AS/3501-6 Graphite/Epoxy and S2/3501-6 Glass/Epoxy," to be submitted for publication.

6. "Textile Fibers for Industry," Owens-Corning Fiberglas Corporation, Toledo, Ohio, 1971.

7. D. F. Adams and B. G. Schaffer, "Micromechanics Predictions Versus Experimental Measurements of Unidirectional Composite Properties," to be submitted for publication.

8. D. F. Adams and M. M. Monib, "Moisture Expansion and Thermal Expansion Coefficients of a Polymer-Matrix Composite Material," Proceedings of the Fourth Conference on Fibrous Composites in Structural Design, San Diego, California, November 1978.

9. D. F. Adams, "Temperature-and Moisture-induced Normal and Shear Stresses at the Fiber/Matrix Interface in Various Composite Materials," Proceedings of the 24th National SAMPE Symposium & Exhibition, San Francisco, California, May 1979.

10. P.D. McLean, R. F. Scott and W. Wieber, "Development of Aromatic Diamides as Cross-Linking Agents," Proceedings of the Second International Conference on Composite Materials, Toronto, Canada, April 1978.

11. D. F. Adams and M. M. Monib, "Contribution of the Polymer Matrix to the Hygrothermal and Mechanical Response of a Composite Material," to be published in The Journal of Rheology.

12. D.E. Walrath and D. F. Adams, "Moisture Absorption Analysis of the Thematic Mapper Graphite/Epoxy Composite Structure," in bound volume entitled Modern Developments in Composite Materials and Structures, ASME Winter Annual Meeting, New York, New York, December 1979.

13. "Addition of Longitudinal Shear Loading to Existing Micromechanics Analysis," Army Materials and Mechanics Research Center Grant, September 1979 - September 1980.

14. "Energy Absorption Mechanisms During Crack Propagation in Metal Matrix Composites," Grant No. NSG 3217, NASA-Lewis Research Center, August 1978 - August 1980.